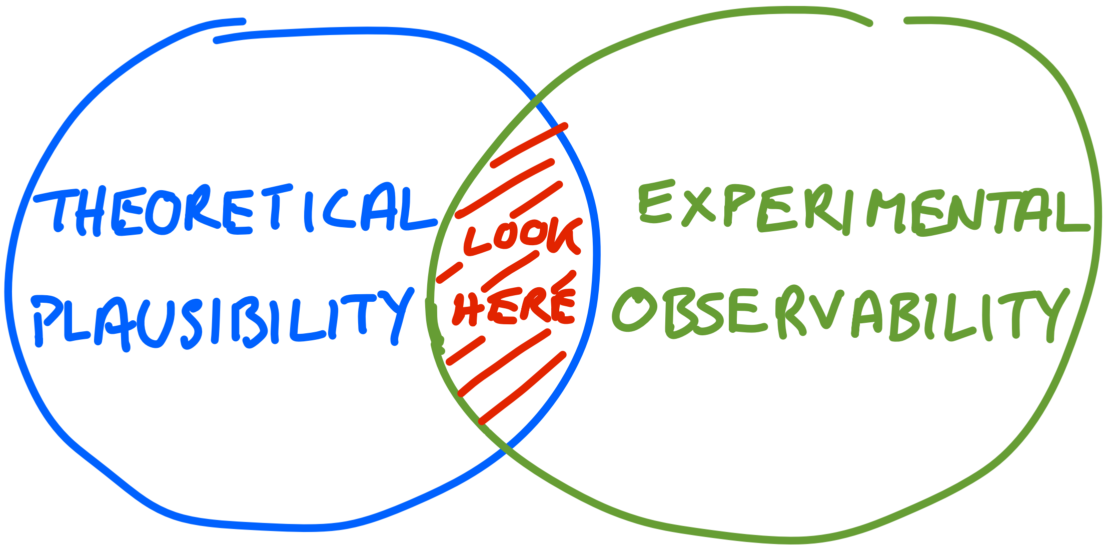
BSM Wishlist

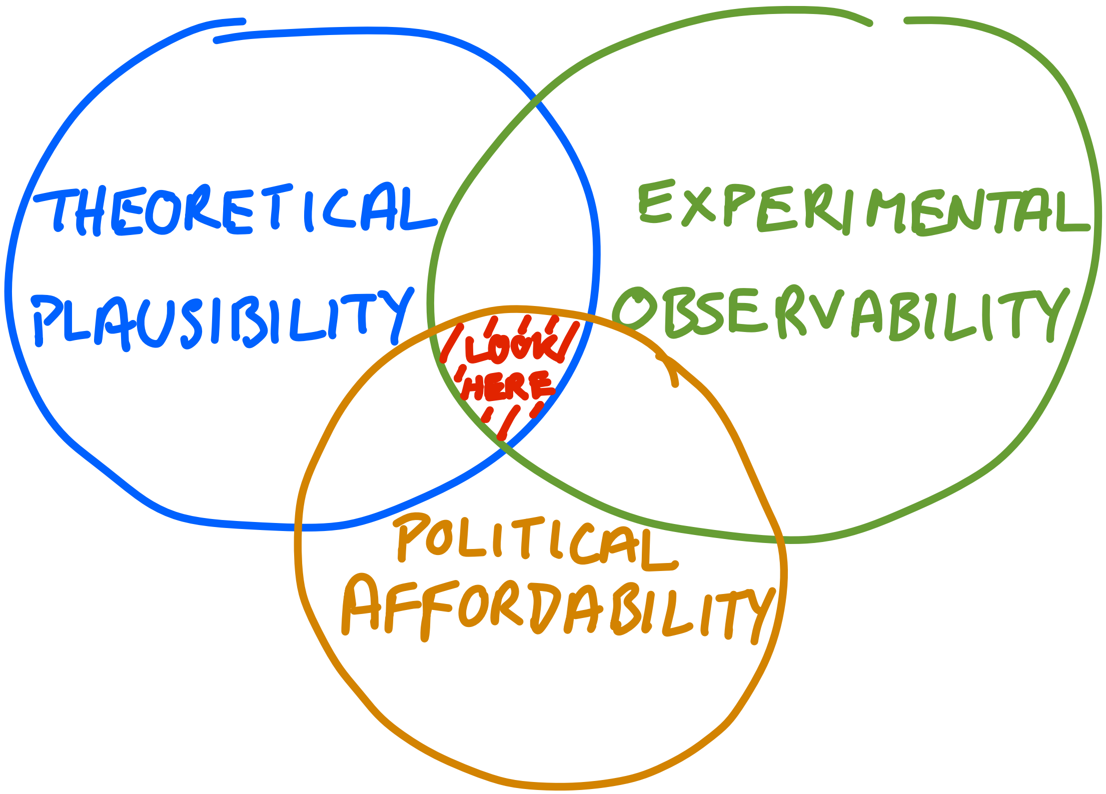
Raman Sundrum, UMD

In collaboration with

Nima Arkani-Hamed, Nathaniel Craig, Patrick Meade, Isobel Ojalvo, and Matthew Reece

July 21, 2020


THEORETICAL PLAUSIBILITY
LOOK HERE
EXPERIMENTAL OBSERVABILITY


THEORETICAL
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LOOK
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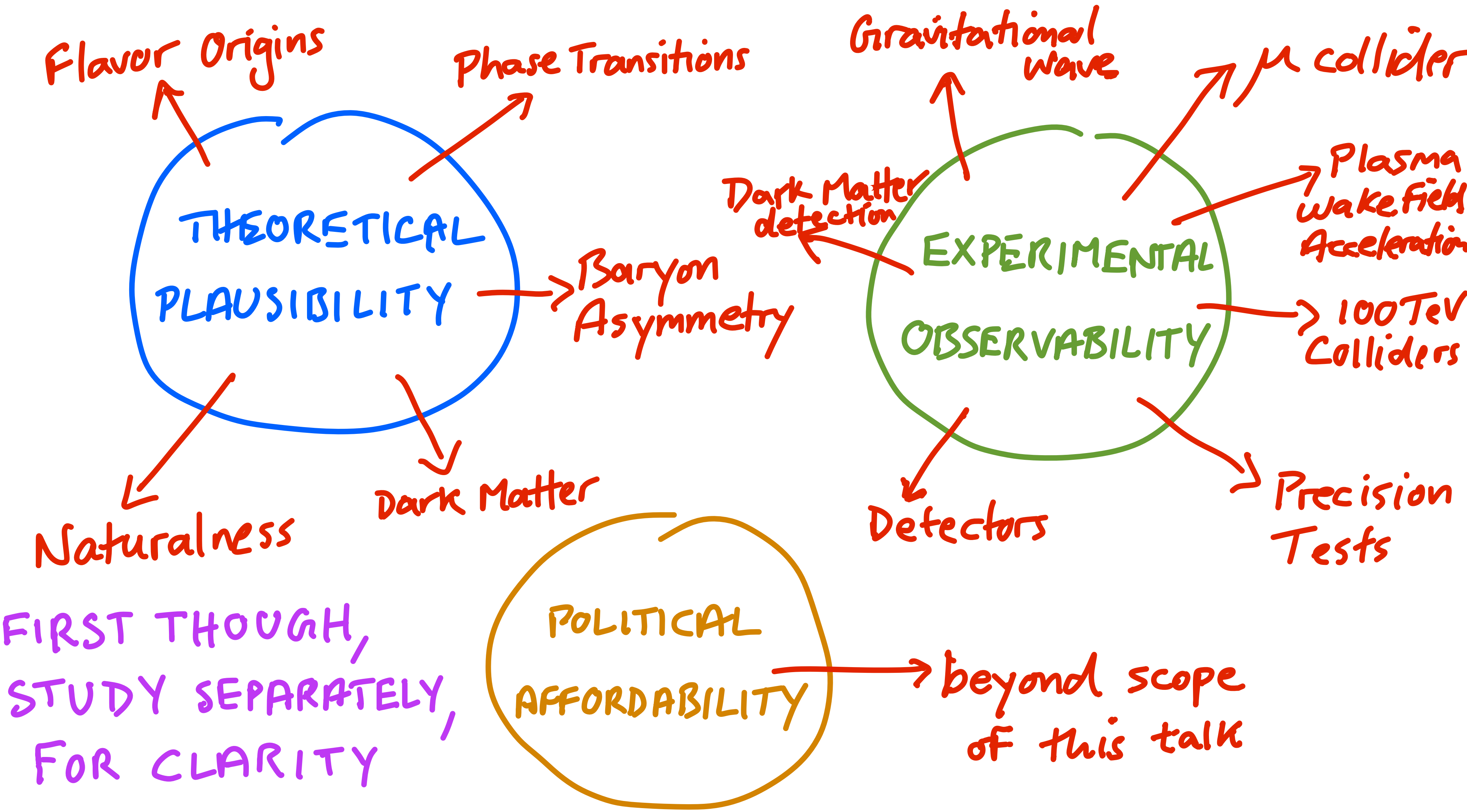
POLITICAL
AFFORDABILITY



THEORETICAL PLAUSIBILITY
Flavor Origins
Phase Transitions
Baryon Asymmetry
Naturalness
Dark Matter
EXPERIMENTAL OBSERVABILITY
Gravitational wave
μ collider
Plasma
Dark Matter detection
100 TeV Colliders
Detectors
Precision Tests
POLITICAL AFFORDABILITY
beyond scope of this talk
FIRST THOUGH, STUDY SEPARATELY, FOR CLARITY

AMBITIOUS, PLAUSIBLE THEORY

By providing aspirational targets

- It helps sharpen arguments for what can be seen and what needs calculated (BSM,SM,Formal theory crossovers)
- Since machines/detectors well beyond current scope are needed, it provides exciting R&D goals for both accelerator and experimental physics
- It can also help focus ***existing*** proposals to see if e.g. detectors can be proposed to address specific questions

Theorists aren't the only ones with ambitious goals of course

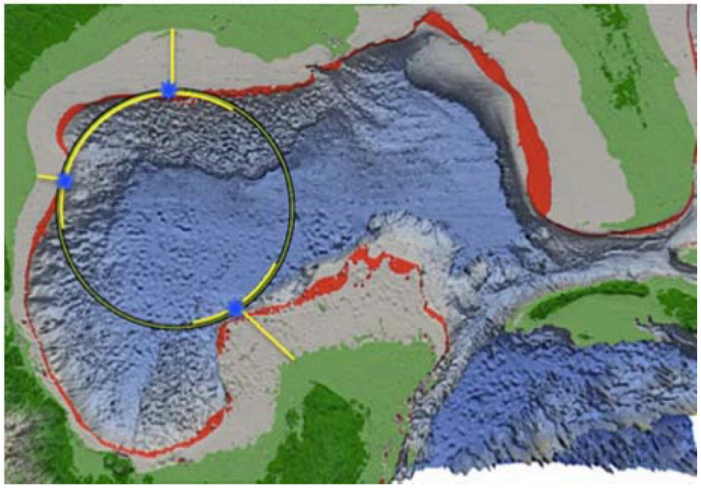


Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron collider. Red =100→200 m isobaths; gray = 0-100 m isobaths; blue = detectors; green = surface topography.

Collider in the Sea: Vision for a 500 TeV World Laboratory

Proceedings, 2nd North American Particle Accelerator Conference (NAPAC2016), P. McIntyre et al

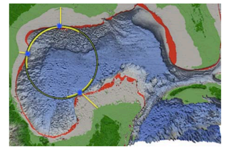


Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron

Collider in the Sea: Vision for a 500 TeV World Laboratory

?

μ or e-collider 30 TeV

Plasma Wake Field Acceleration

FCC-hh/SPPC

μ-collider 14 TeV

Physics Potential

CLIC

FCC-ee/CEPC

ILC

μ-collider 125

R&D challenge

For now we'll start with some theory goals and see where they get us…

Subdividing what we've come up with so far

Three main categories with lots of overlap

Completing the SM/Measuring Higgs

One probably most relevant for this session

- The Higgs ***is*** the strangest part of the SM
- All of its couplings and major BF should get to 5σ
- However - observation doesn't imply better than O(1) precision
- What precision do we want? Need extra theory motivation e.g:
  - Electroweak Phase Transition, Flavor, Naturalness

BSM Motivations

- Naturalness
  - Compositeness
  - SUSY
  - Neutral Naturalness
- Dark Matter
- Flavor, ~~CP~~
- Hidden Sectors
- Baryogenesis

The questions remain even with the success of LHC

some even more so than before

There are also new *potential* answers being developed

that have qualitatively and quantitatively different pheno

Complementarity with other Frontiers

While slow at the start, the energy frontier is needed to ultimately "win the race"

Nevertheless if we get indirect hints from existing

or planned experiments its important to know how to test them!

Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

Examples

Completing the SM/Higgs

Triple Higgs Coupling and Beyond

The unmeasured SM quartic controls both the triple and quartic Higgs couplings

It would of course be important to measure these independently!

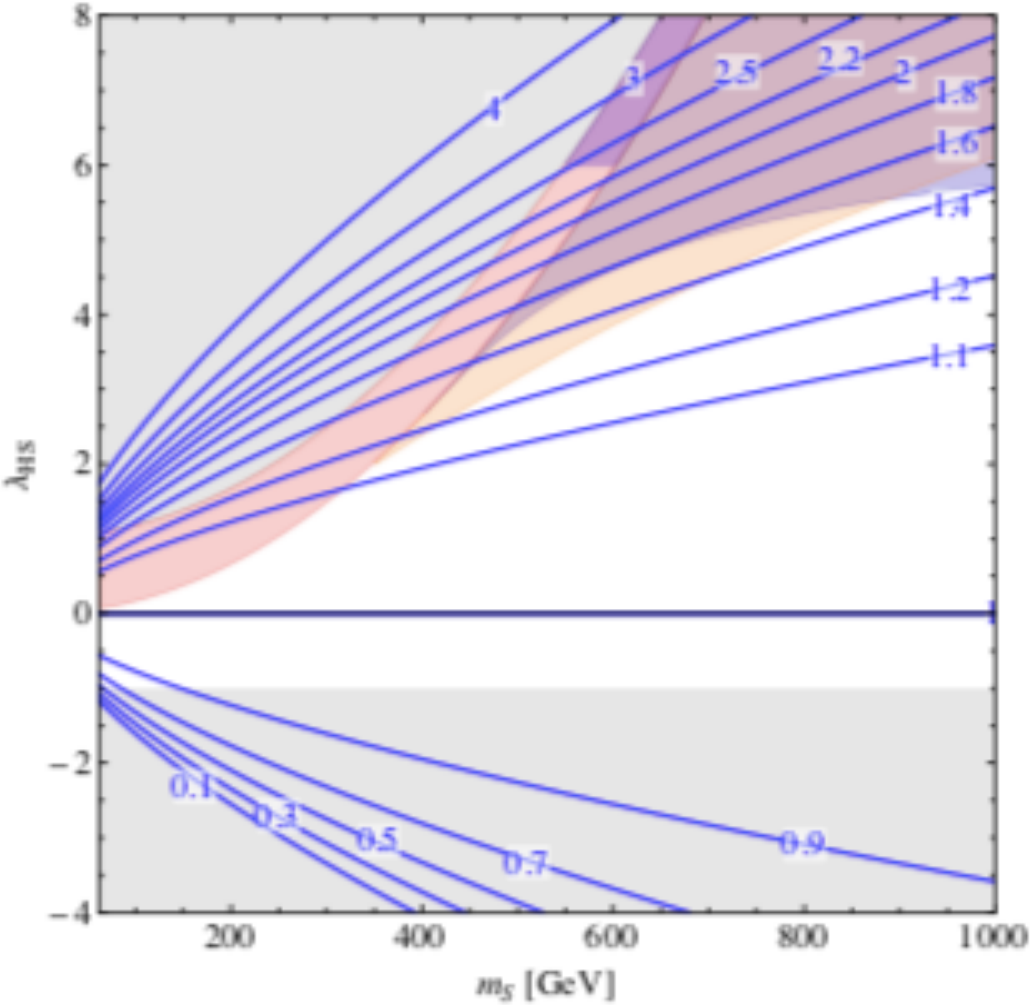
λ_3 first target since di-Higgs is easier to produce

How much precision is needed?

Can take random models or ask about ***theory*** question like Electroweak Phase Transition

Triple Higgs and EWPT

Strong Fir



sover

δ

%

Lore - I

h Triple Higgs

Triple Higgs and EWPT

Strong First Order Phase Transition

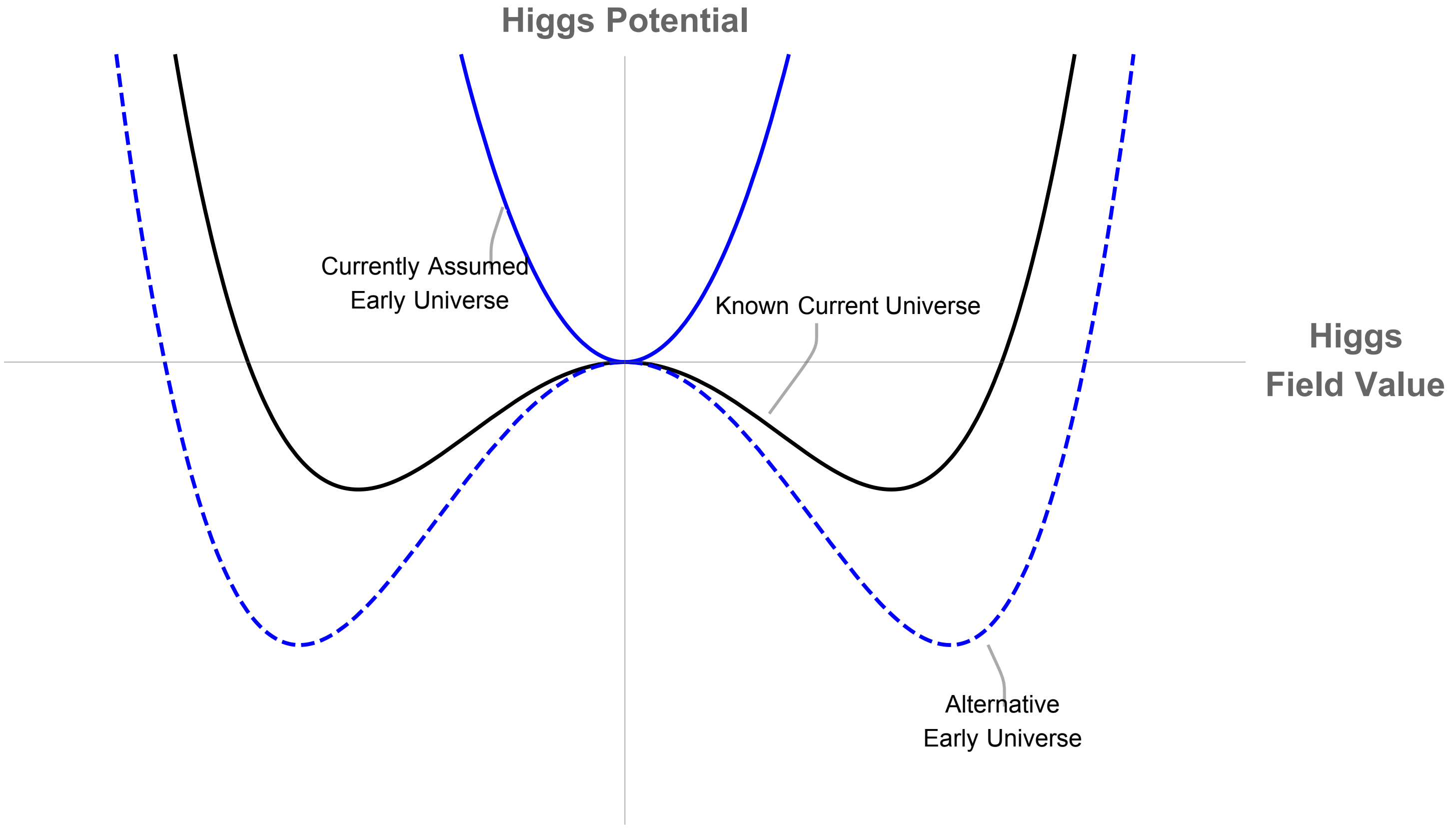
$$\delta\lambda_3 \gtrsim 10\%$$

SM Crossover

$$\delta\lambda_3 \sim 0\%$$

Lore - Easy to distinguish 2 possible early universes with Triple Higgs

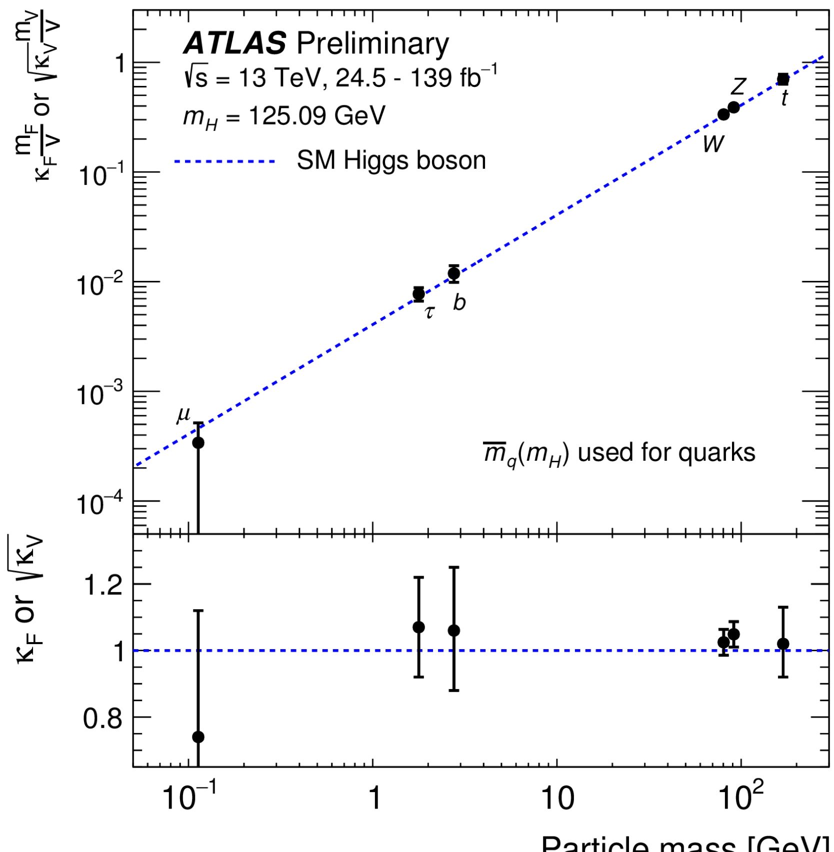
Theory Marches Forward - Turns out 3 cases



Three qualitatively DIFFERENT histories of our universe

In principle need $\delta\lambda_3 \ll 1\%$ to distinguish

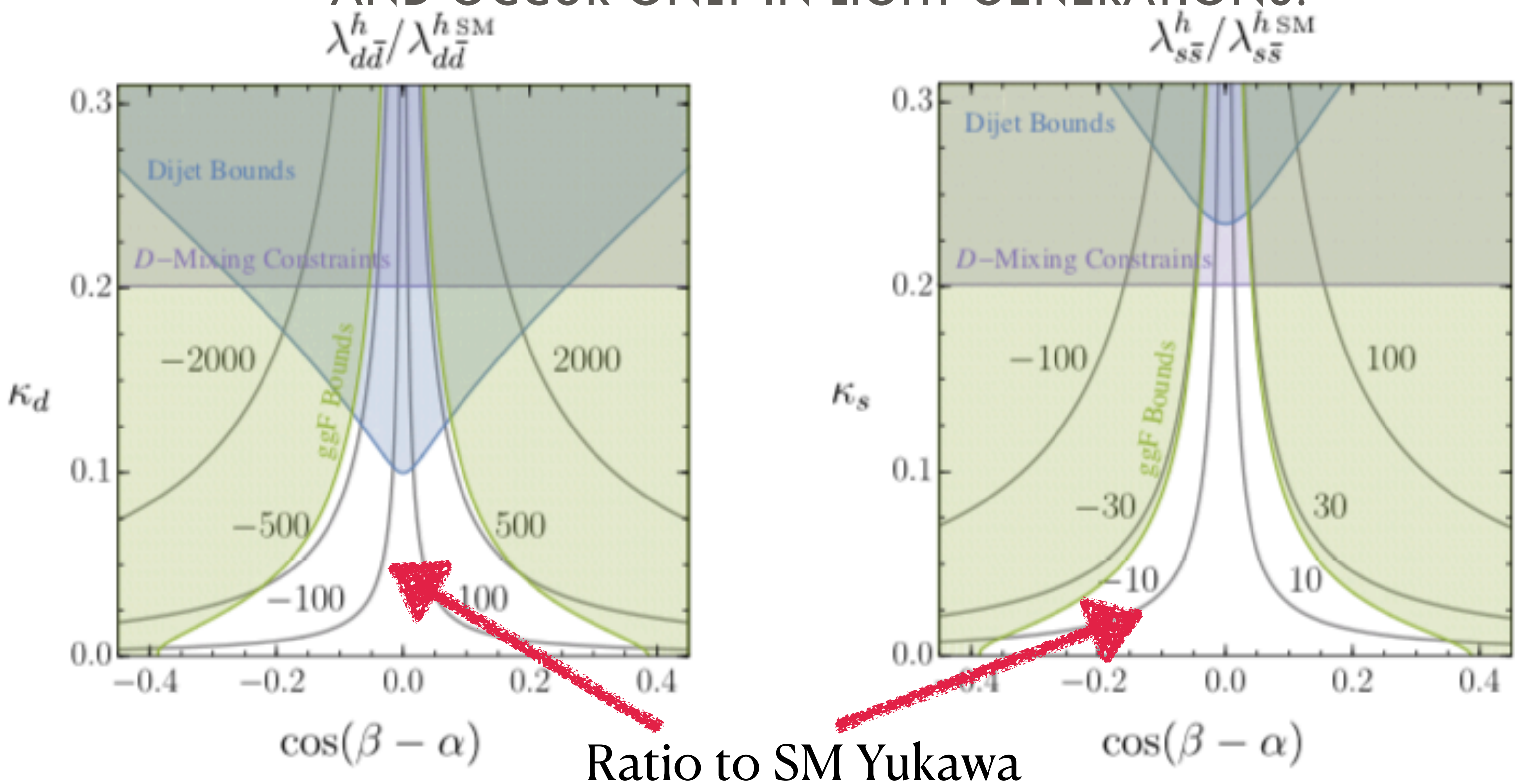
Higgs and Flavor



We're used to thinking that biggest deviations should be for heaviest particles

Motivation - MFV and Naturalness - Not a lot telling us we ever even need light Yukawas

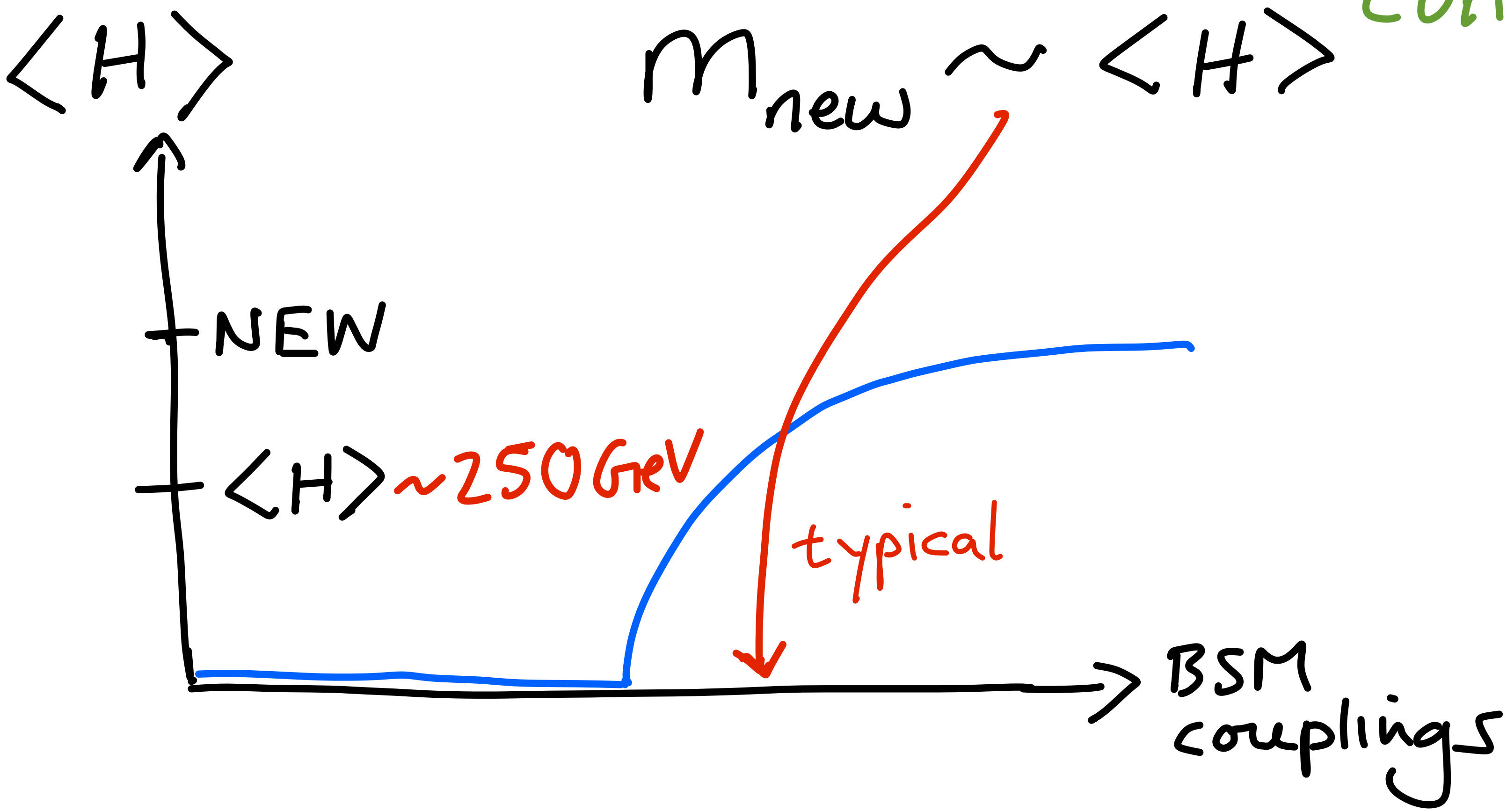
BUT... THERE ARE FLAVORFUL MODELS
WHERE THE MASS/COUPLING RATIO OF **OUR HIGGS** CAN
BE PARAMETRICALLY DIFFERENT, SATISFY CONSTRAINTS,
AND OCCUR ONLY IN LIGHT GENERATIONS!



BSM Motivations

NATURALNESS is vital consideration!

$m_{new} \sim \langle H \rangle$



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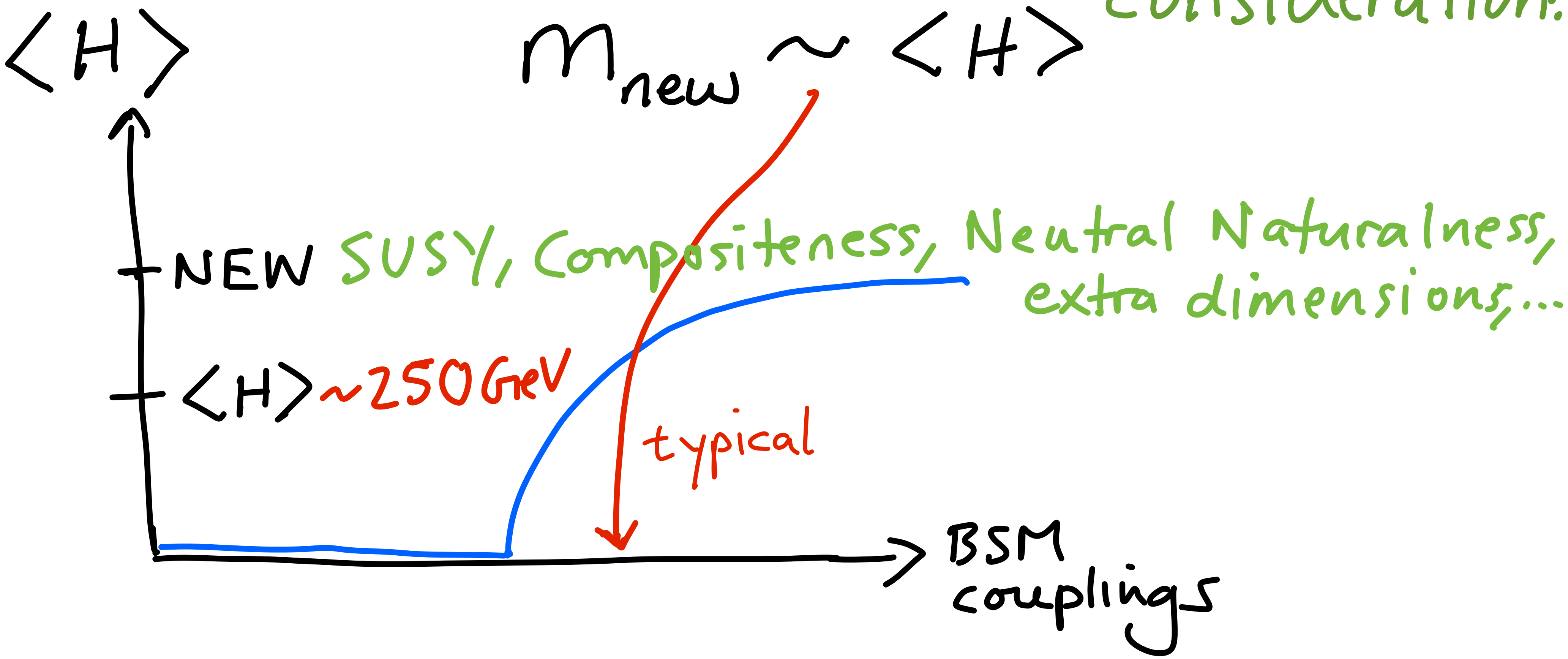

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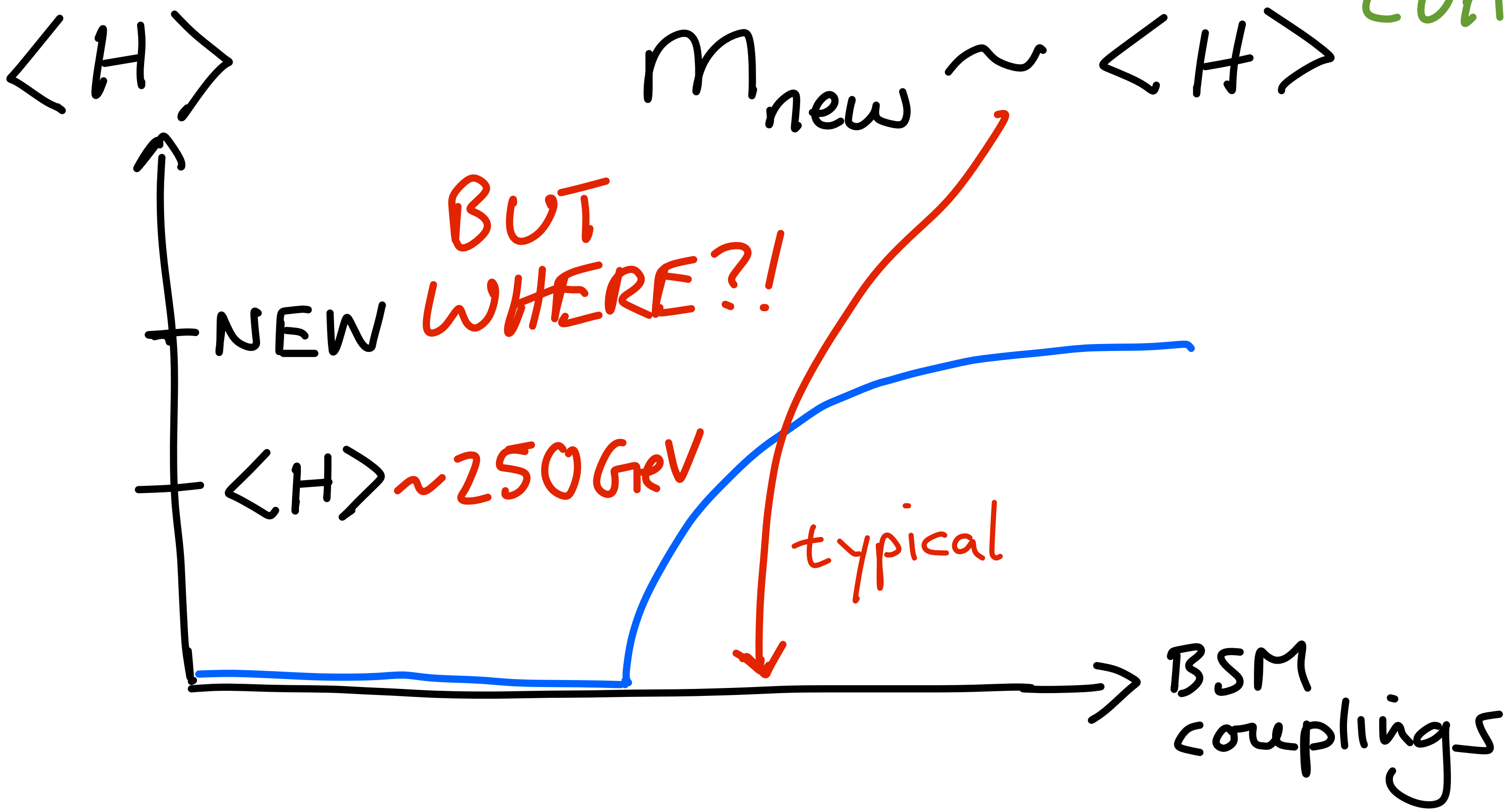
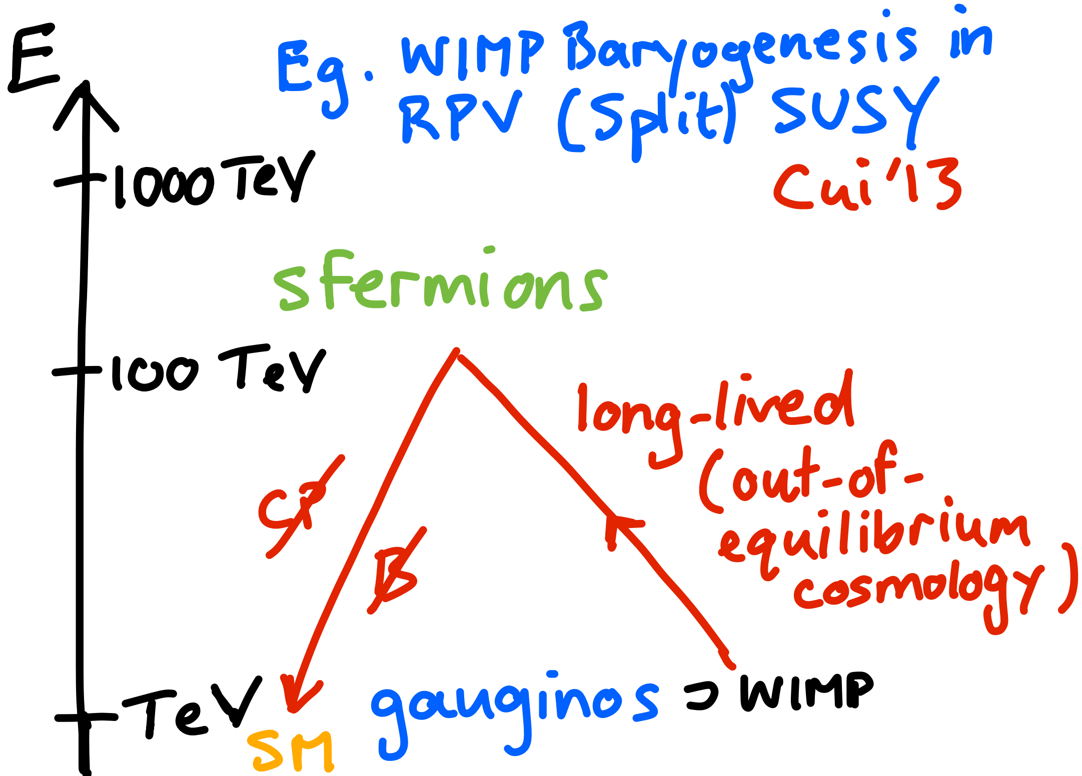


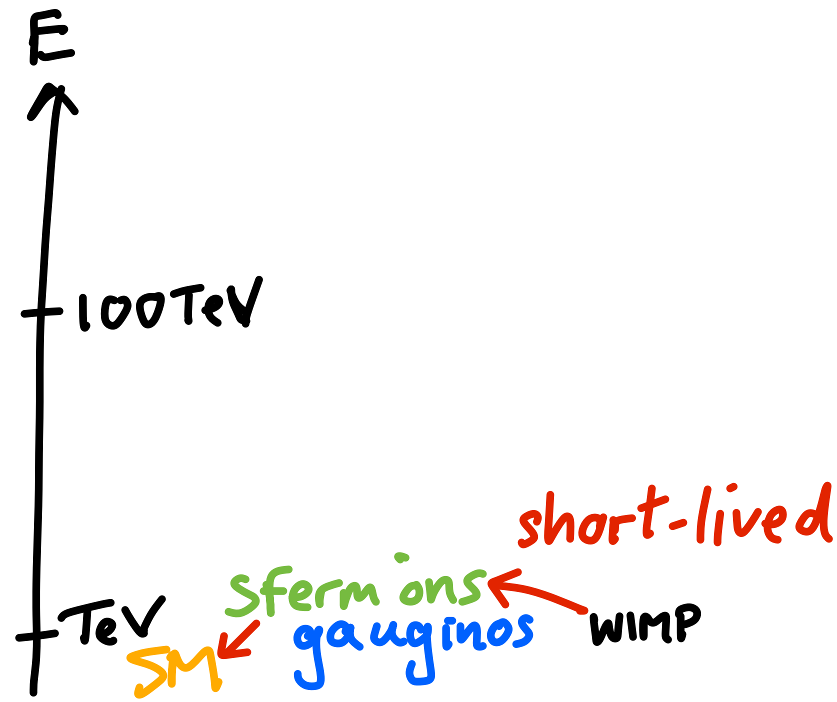
FRUSTRATED NATURALNESS
(due to Anthropic Selection)

Eg. WIMP Baryogenesis in RPV (Split) SUSY

Cui '13



"Meso-tuned" but
successful baryogenesis



"Natural", but
unsuccessful baryogenesis

Effectively,

NATURALNESS IS NOT A 0/1 THING!

But hard to track source of FRUSTRATION

INTERACTING SCALARS ARE RARE!

We observe:

LOTS of spin $1/2$, 1 fundamental fields

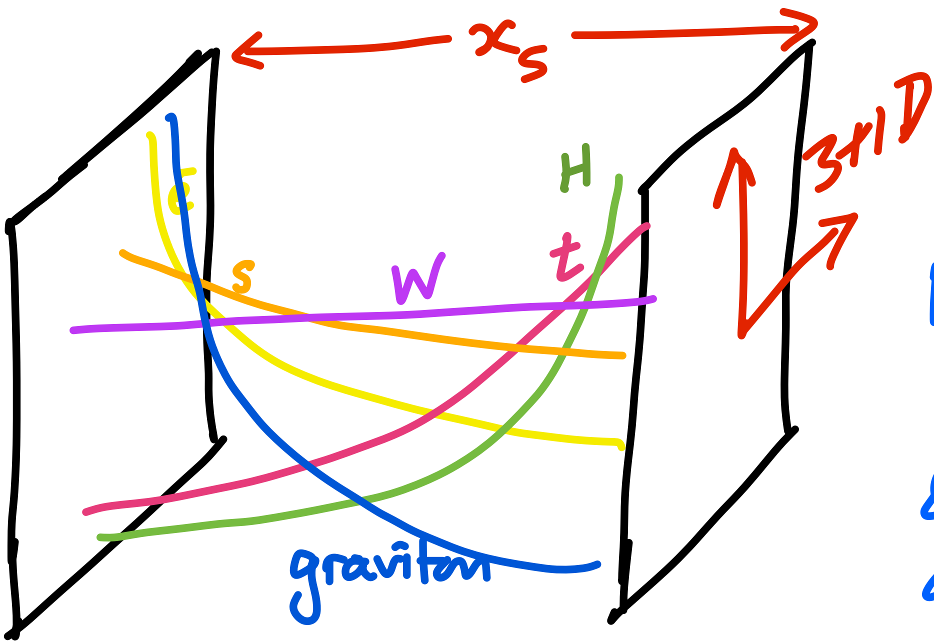
Massless spin 2 (theoretically must be) GRAVITY

Lots of composite (hadronic) fields of all spins. Includes spin-0 Eg. π^+, but m_{π^+} beautifully NATURAL due to QCD compositeness.

HIGGS BOSON IS TRULY EXCEPTIONAL!

COMPOSITE HIGGS

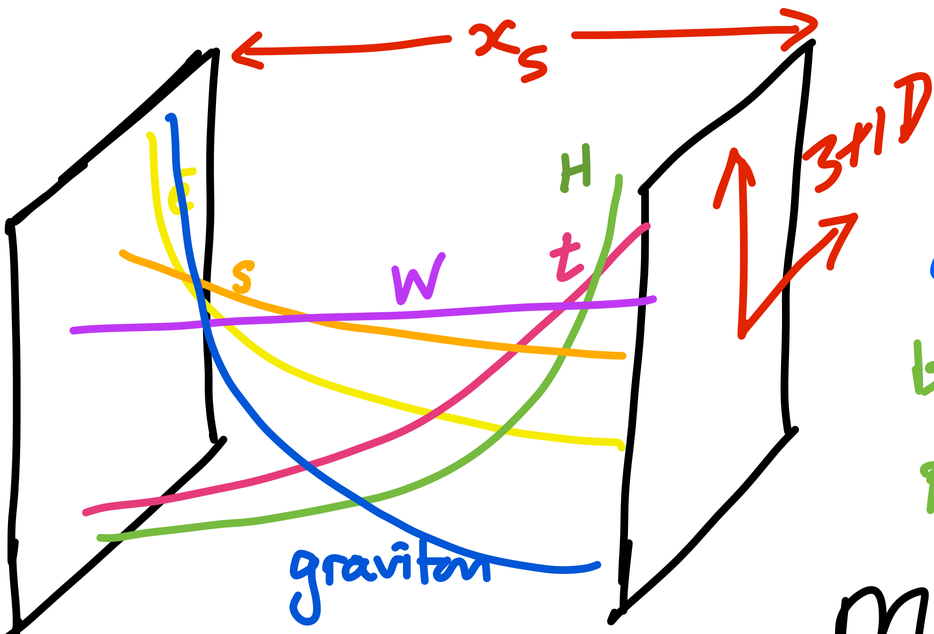
This strong-coupling problem can be geometrized via AdS/CFT into WARPED EXTRA DIMENSIONS



Extra-dimensional wavefunction overlaps
⇒ attractive mechanism behind observed FLAVOR STRUCTURE
& ELECTROWEAK HIERARCHY
& UNIFICATION

COMPOSITE HIGGS

This strong-coupling problem can be geometrized via AdS/CFT into WARPED EXTRA DIMENSIONS



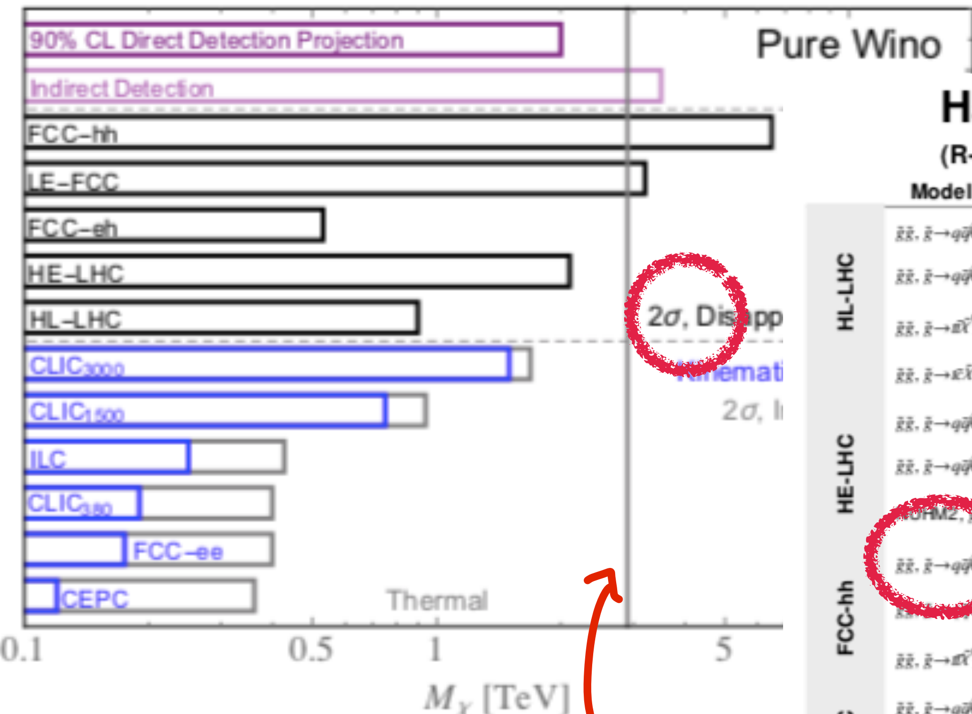
SIMPLEST MODELS (fewest theoretical epicycles) CONSTRAINED by ~~FLAVOR~~ ~~CP~~ PRECISION TESTS

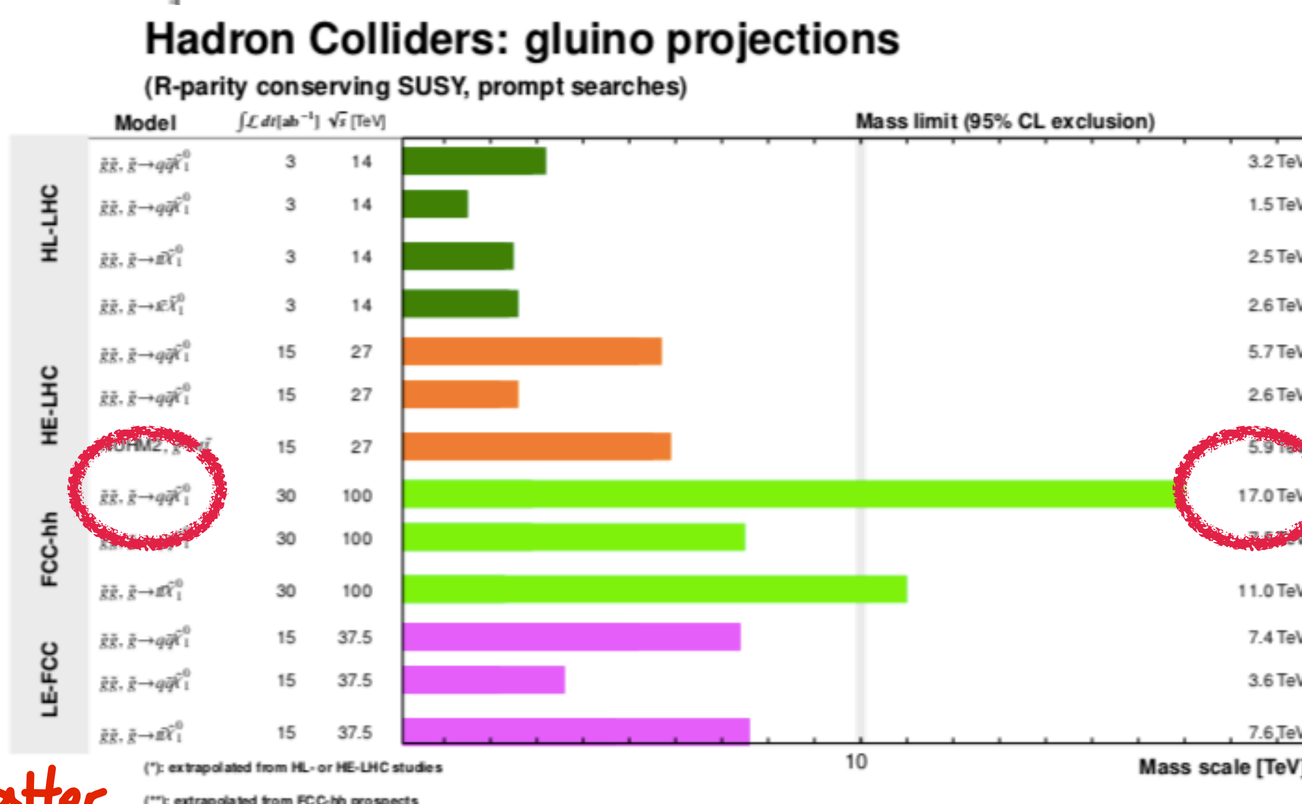
$m_{\text{Kaluza-Klein excitations}} \gtrsim$ 10s – 100 TeV

Supersymmetry

Simple option: Mini-Split

Wino as Thermal Relic implies ~ 30 TeV Gluino



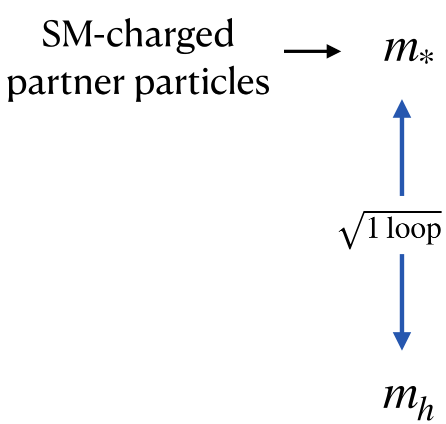


Simple Thermal relic Dark Matter

Naturalness in the dark

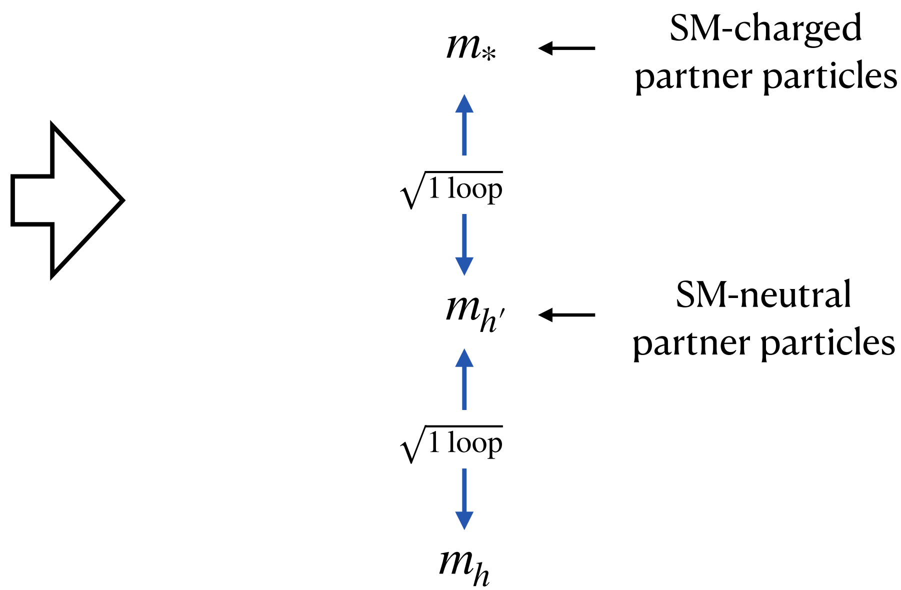
Hidden sector resolutions of the little hierarchy problem

Conventional Naturalness



Natural scale of new SM-charged particles raised by ~ 4π

Neutral Naturalness (Twin Higgs, ...)



Naturalness in the dark

What is required for discovery?

m_* $\longrightarrow$

- SM-charged states @ $m_* \lesssim (\text{loop}) \times \mathrm{m_h} \sim 20\,\mathrm{TeV}$
- Requires pp machine @ $\sqrt{s} \sim 300\,\mathrm{TeV}$

$\updownarrow \sqrt{1\ \text{loop}}$

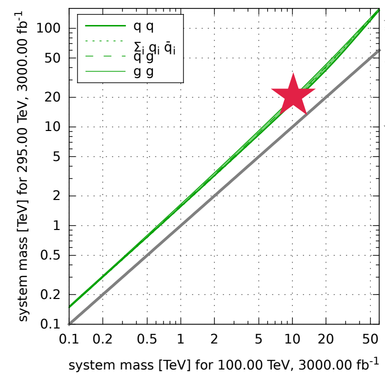
$m_{h'}$ $\longrightarrow$

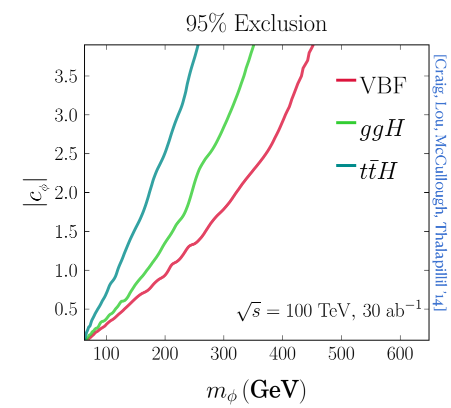
- SM-neutral states between 0.1-10 TeV
- *Challenging target*; 100 TeV reach ~200 GeV

$\updownarrow \sqrt{1\ \text{loop}}$

m_h $\longrightarrow$

- Higgs coupling deviations at 1% level
- Higgs decays to LLPs at 0.01% level





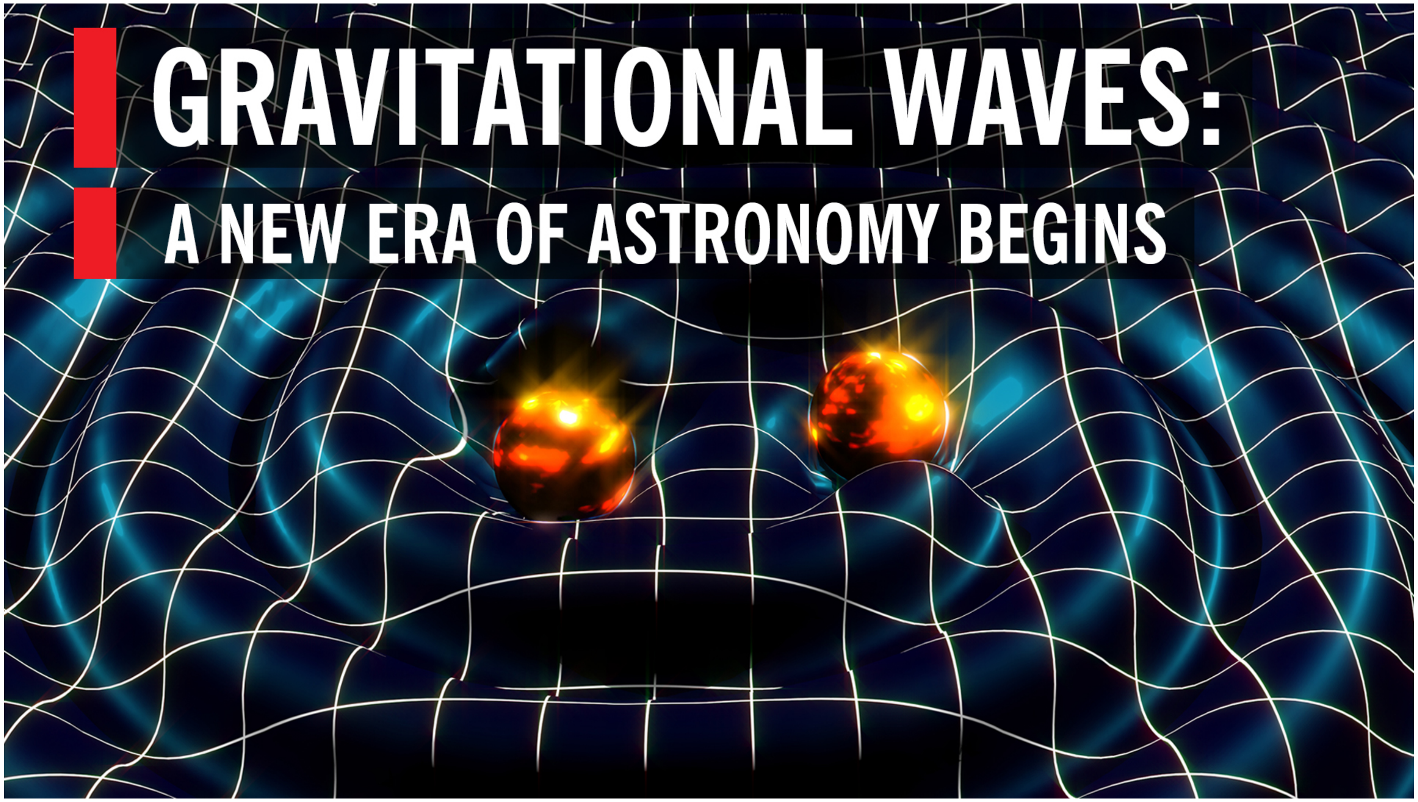
Complementarity

Gravitational Waves From Phase Transitions

Gravitational waves are the only direct observational probe before CMB in Cosmology

Gravitational Waves From Phase Transitions

Gravitational waves are the only direct observational probe before CMB in Cosmology



AND THEY ARE HERE!!

Gravitational Waves From Phase Transitions

Gravitational waves are the only direct observational probe before CMB in Cosmology

Search for the isotropic stochastic background using data from Advanced LIGO's second observing run

The LIGO Scientific Collaboration and The Virgo Collaboration

(Dated: September 9, 2019)

The stochastic gravitational-wave background is a superposition of sources that are either too weak or too numerous to detect individually. In this study we present the results from a cross-correlation analysis on data from Advanced LIGO's second observing run (O2), which we combine with the results of the first observing run (O1). We do not find evidence for a stochastic background, so we place upper limits on the normalized energy density in gravitational waves at the 95% credible level of $\Omega_{GW} < 6.0 \times 10^{-8}$ for a frequency-independent (flat) background and $\Omega_{GW} < 4.8 \times 10^{-8}$ at 25 Hz for a background of compact binary coalescences. The upper limit improves over the O1

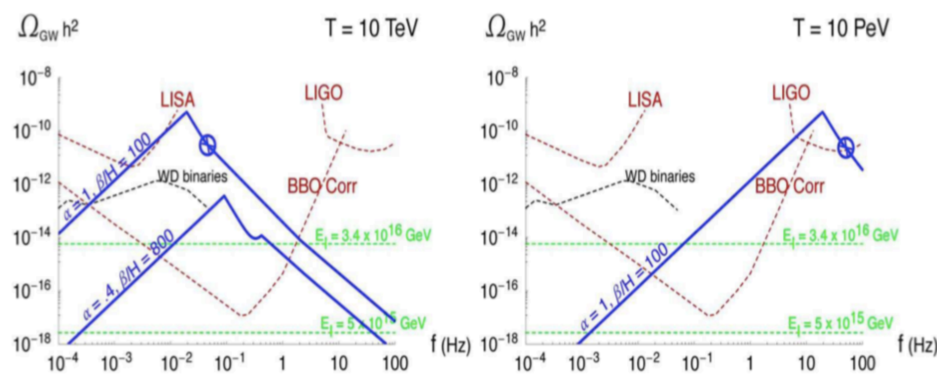
Stochastic Gravitational Wave Signal is Challenging (and astrophysics constributions!)-

Would it be trusted as signal for BSM without complementary measurements?

Gravitational Waves From Phase Transitions

LIGO frequency band $f \sim \mathcal{O}(10^2)\mathrm{Hz}$

LISA frequency band $f \sim \mathcal{O}(10^{-3})\mathrm{Hz}$



Therefore if something is *observed* with future LIGO runs it points to high (PeV) scales!

LISA 2030s timescale fills in to lower, but still favors higher scales $\gg$ TeV

This would be v. exciting cosmo discovery

Could we study microphysics in the "lab"?

CAN WE EXPLICITLY DISCOVER NEW PHYSICS underlying anomalies that could easily appear in rapidly improving ~~CP~~ & ~~flavor~~ precision tests?

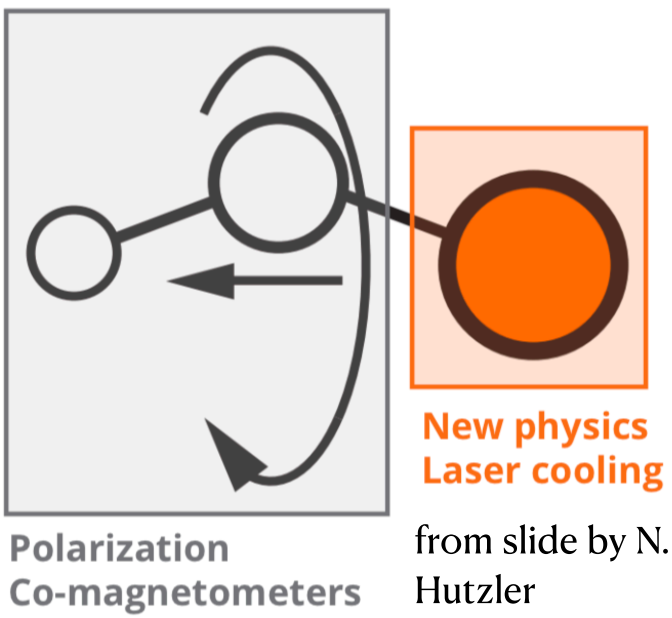
BSM ~~CP~~

Complementarity: Electric Dipole Moments (EDMs)

Precision on the Horizon

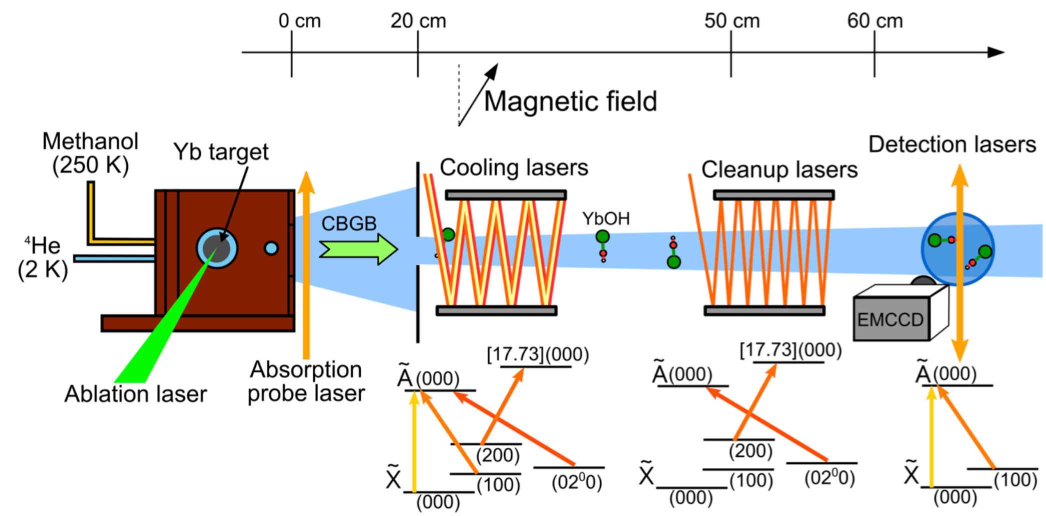
One of several parallel approaches:

Polyatomic Molecules (e.g., YbOH)
Hutzler, Kozyryev 1705.11020



from slide by N. Hutzler

?



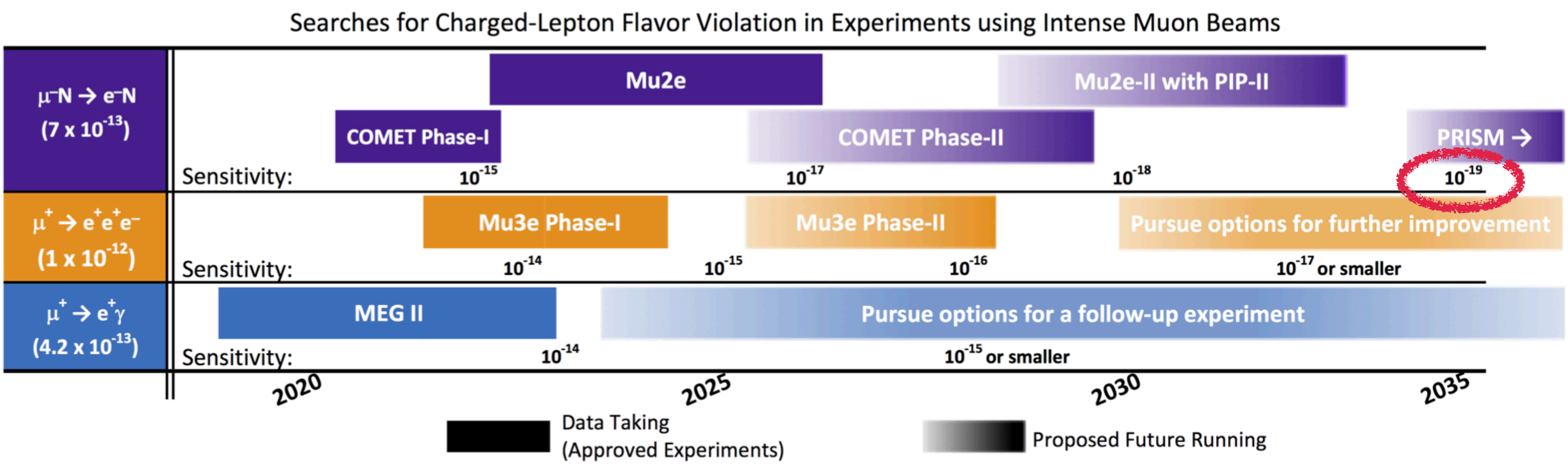
Laser cooling achieved (Augenbraun et al., 1910.11318)

Electron EDM: $10^{-29} e\,\mathrm{cm} \longrightarrow 10^{-32} e\,\mathrm{cm}$ **!**

BSM ~~FLAVOR~~

Complementarity: Charged Lepton Flavor Violation (CLFV)

Precision on the Horizon



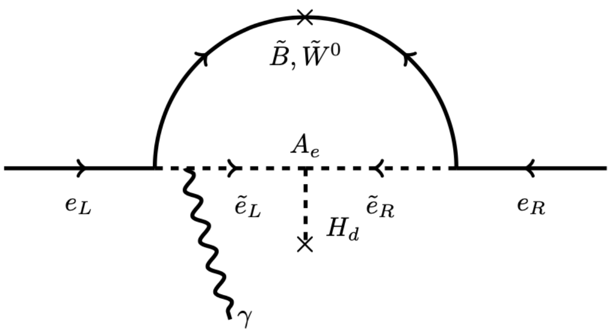
Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations

Complementarity: Physics Reach

The Bottom Line: Probe 10s of TeV to PeV Energy Scales!

EDM, 1-loop

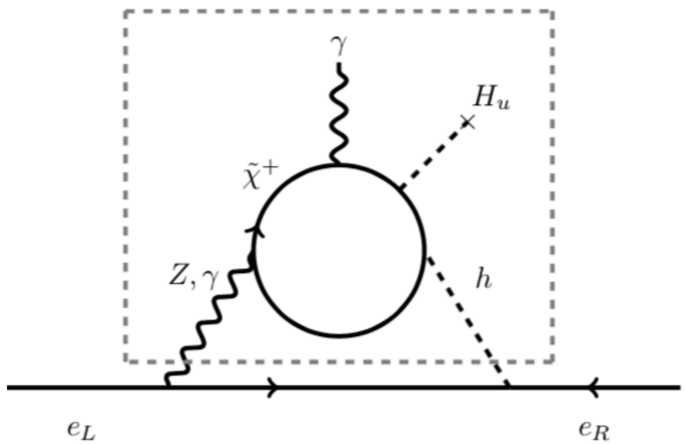
electron-flavored



10^{-32} e cm $\Longrightarrow$ ~ **1 PeV (!)**

EDM, 2-loop Barr-Zee

Anything Higgs+EWK



10^{-32} e cm $\Longrightarrow$ ~ **50 TeV (!)**

(w/ electron Yukawa spurions on all diagrams)

μ→e, 1-loop, flavor violating

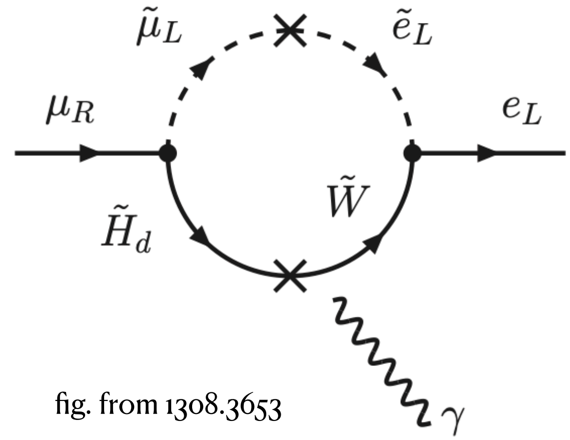


fig. from 1308.3653

Altmannshofer, Harnik, Zupan

10^{-19} on Al $\Longrightarrow$ ~ **50+ TeV (!)**

Conclusion - Snowmass is about the physics

As part of the process let's reflect on what we really know thus far and what we'd really need to push further

As we've seen just from a few physics examples - lots of options pushing to much higher energies and more precision than current benchmarks

We will have some sort of document soon, but we encourage theorists, experimentalists, and accelerator physics to join in these future dreaming efforts!